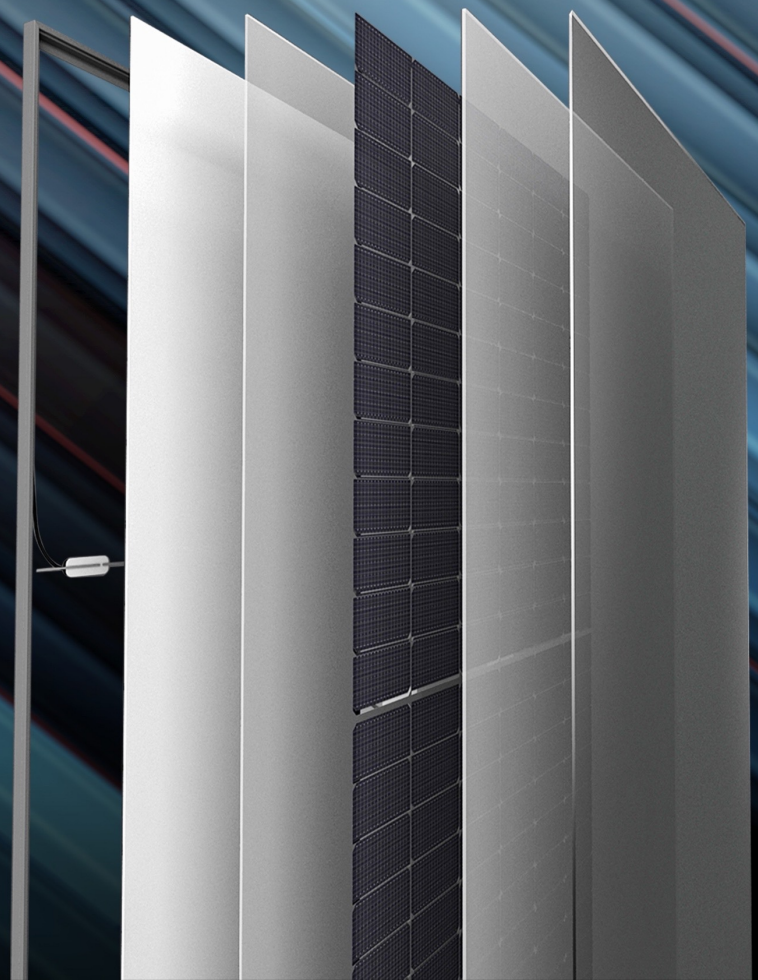
Challenges & Experiences in Scaling up TOPCon n-Type Manufacturing



Johanna Bonilla

Technical Product Manager Europe

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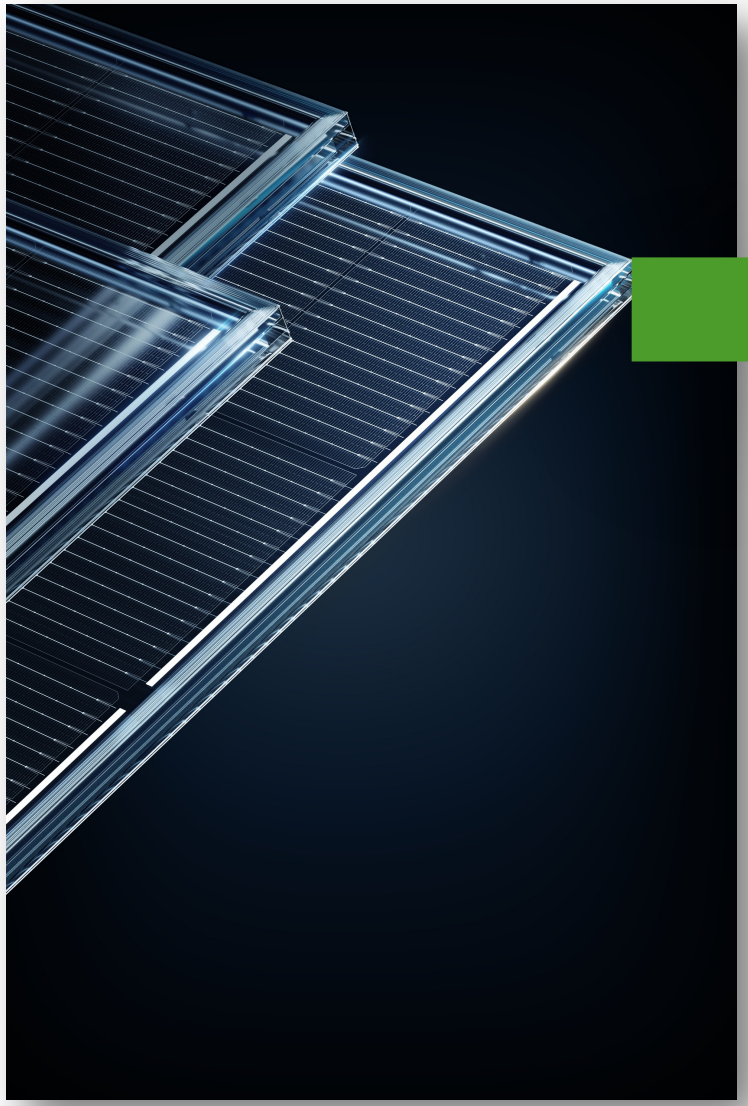


Jinko Performance:

Global Leader

150GW
Delivered
* 2023 Q1

No.1
2016-2019
Module Shipments

25
World Records

110GW
Total Module Capacity
* 2023 Q4

55GW
N-type Module Capacity
* 2023 Q4

15%
Market Share

* *Data as of 2023 Q2

Global Leader in Technological Innovation

1702
Authorized Patents

2278
R&D Team

409
Patents applications

2.637B (CNY)
R&D Investments

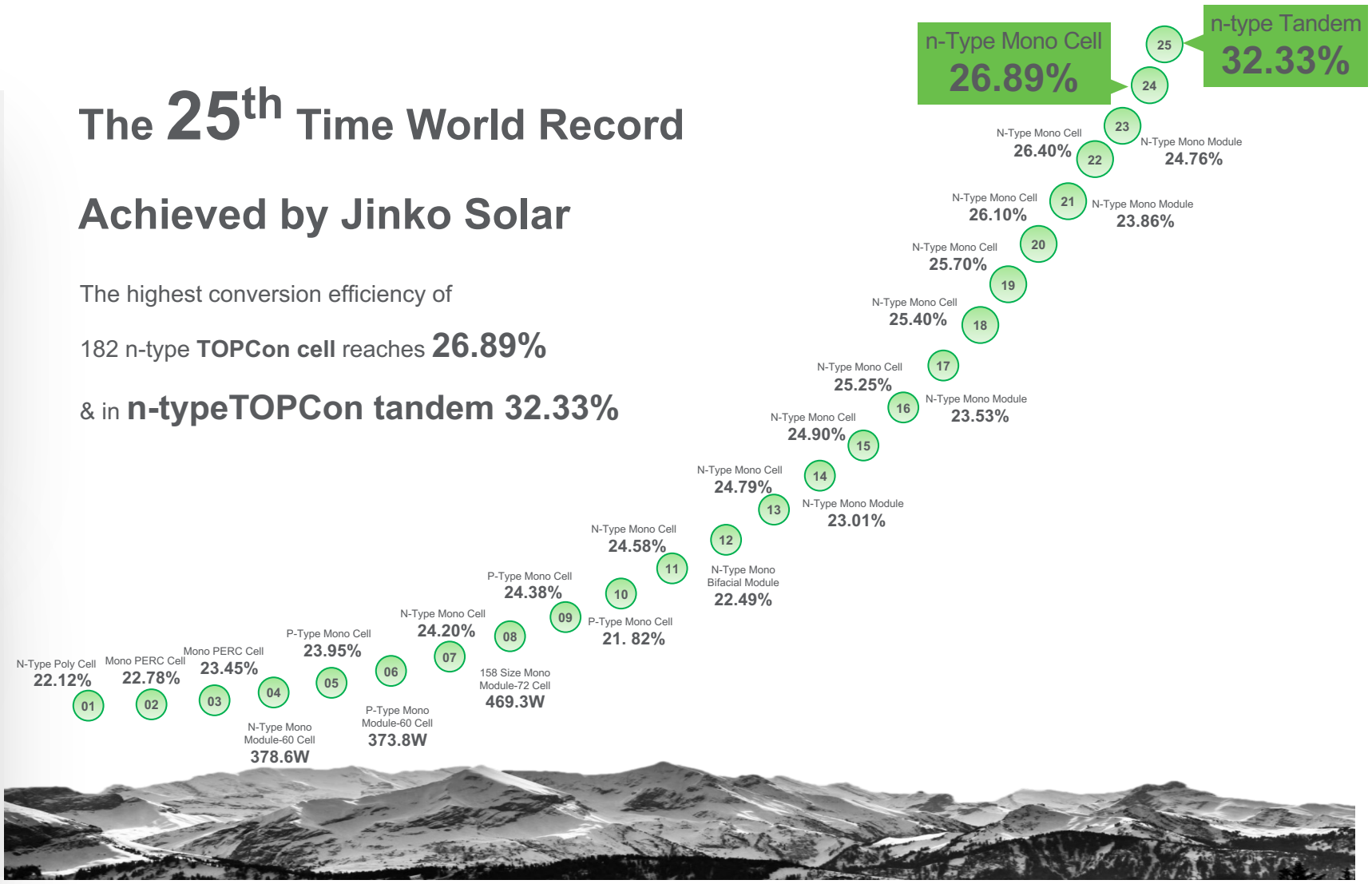
The 25th Time World Record

Achieved by Jinko Solar

The highest conversion efficiency of

182 n-type **TOPCon cell** reaches **26.89%**

& in **n-typeTOPCon tandem 32.33%**



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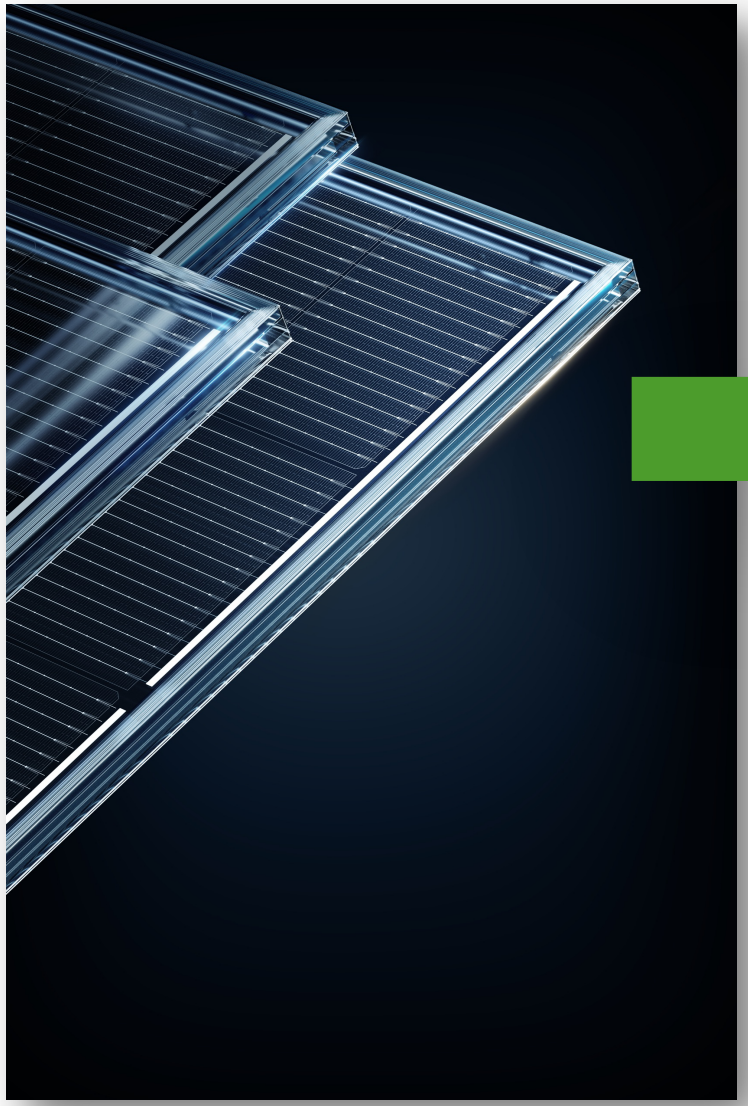
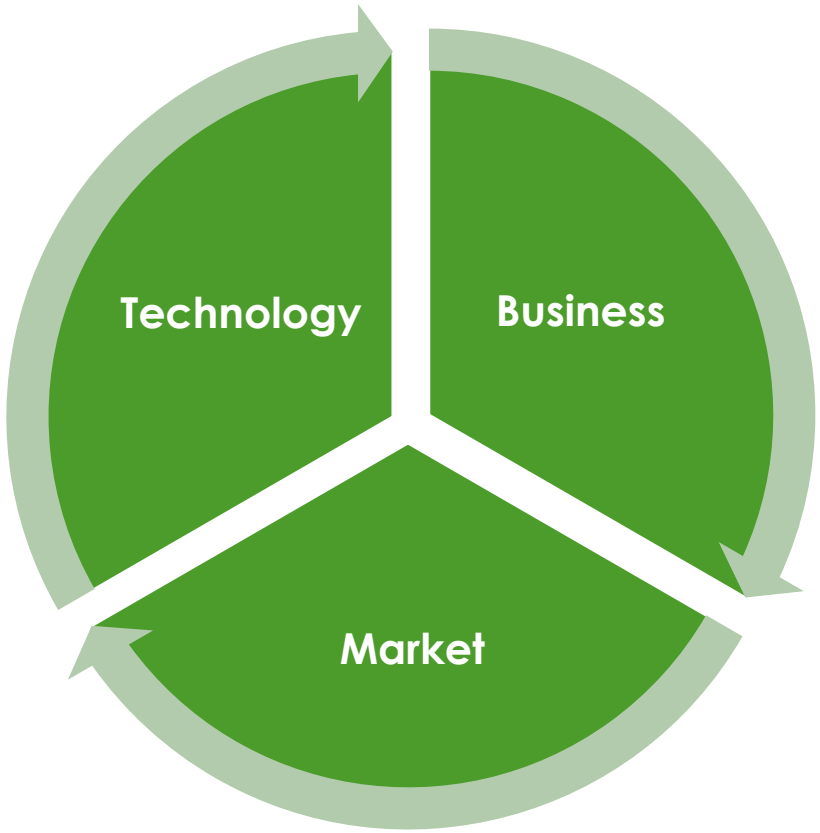


Technical Roadmap: Why TOPCon?

Higher Theoretical Limits
η =28.7% vs. Others[1,2]

Mass Production Viability
Lowered delamination, hotspot, and moisture risks

Maturity & Compatibility
PERC expierence



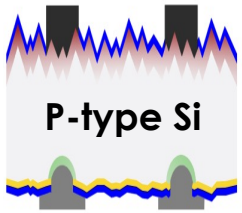
Costs
Supply Chain
Operational Efficiency

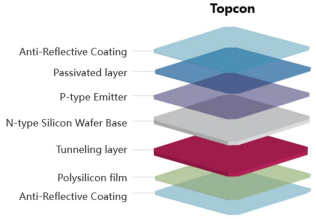
Market Demand & Trends
Regulatory Landscape

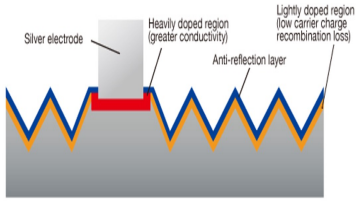
[1] Brendel, R., Rienaecker, M. & Peibst, R. 2016, "A quantitative measure for the carrier selectivity of contacts to solar cells", Proc. 32nd EU PVSEC, Munich, Germany, doi:10.4229/EUPVSEC201620162CO.4.1.
[2] Brendel, R. & Peibst, R. 2016, "Contact selectivity and efficiency in crystalline silicon photovoltaics", IEEE J. Photovolt., Vol. 6, No. 6, pp.1413–1420, doi:10.1109/JPHOTOV.2016.2598267.

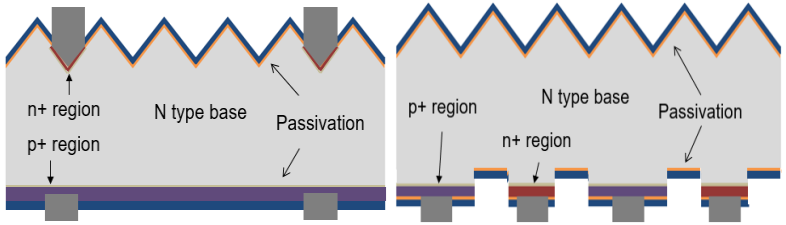
Technical Roadmap: Development trend

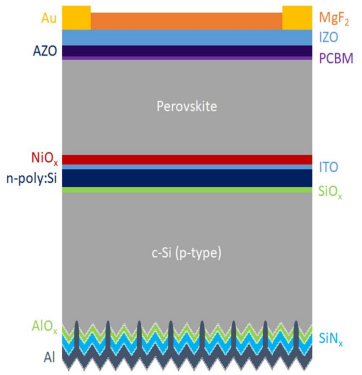
BSL	2022	2023	2024	2025	2026-2027 Expected
23.45%	25~25.2%	25.5~25.8%	26.2~26.5%	26.8~27.0%	Max Eff. >32.0%
0	1	2	3	4	5
PERC P-type Cell	TOPCon N-type Cell	TOPCon+ Selective Emitters	TOPCon Full Passivated 1.0	TOPCon Full Passivated 2.0	TOPCon Tandem Cell











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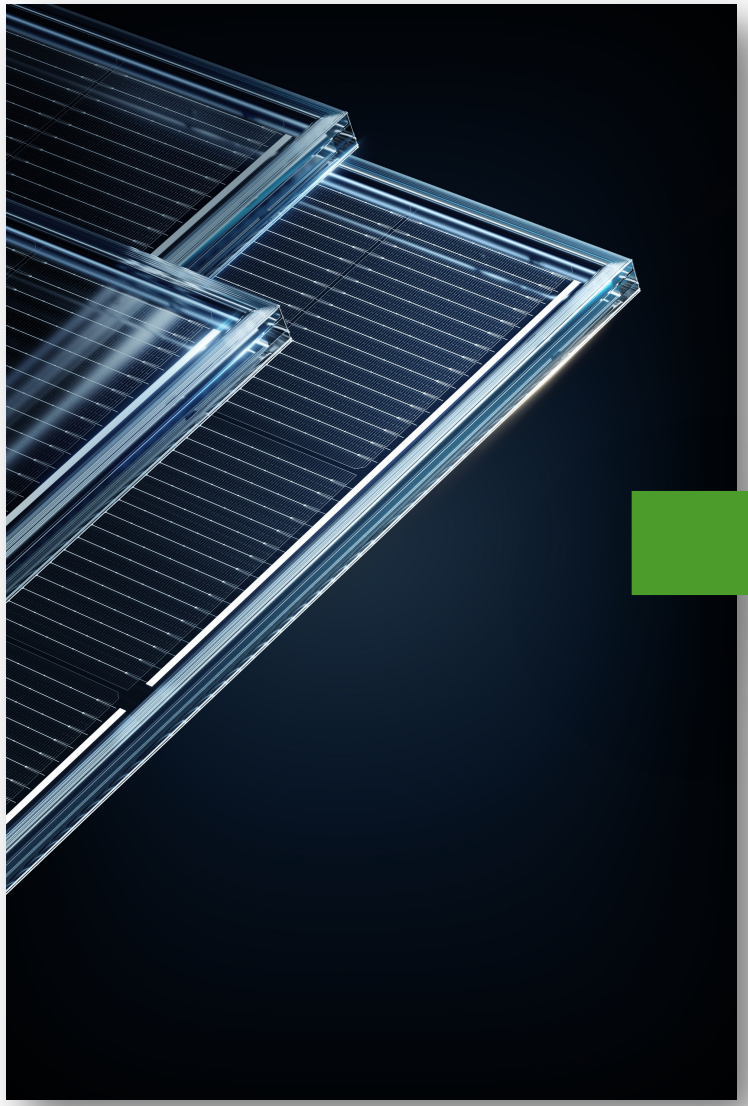
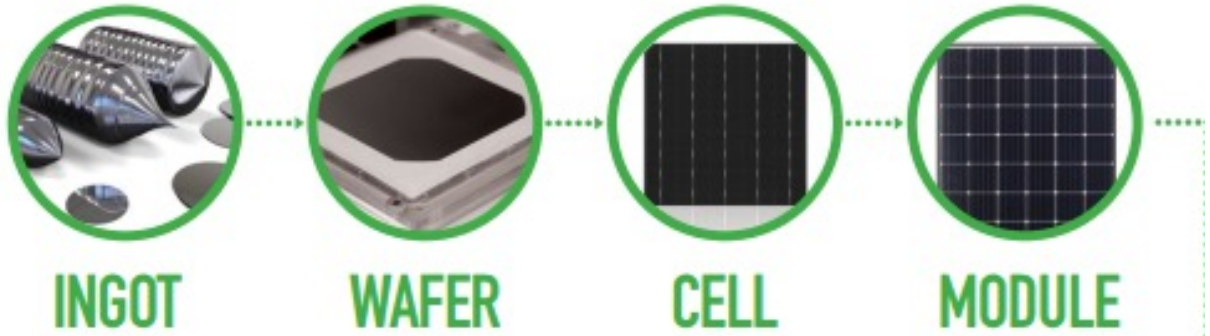


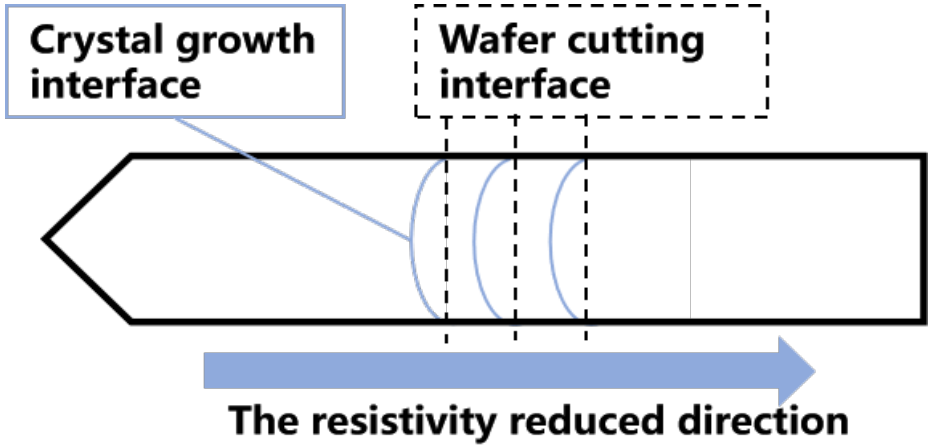
Vertically Integrated Production



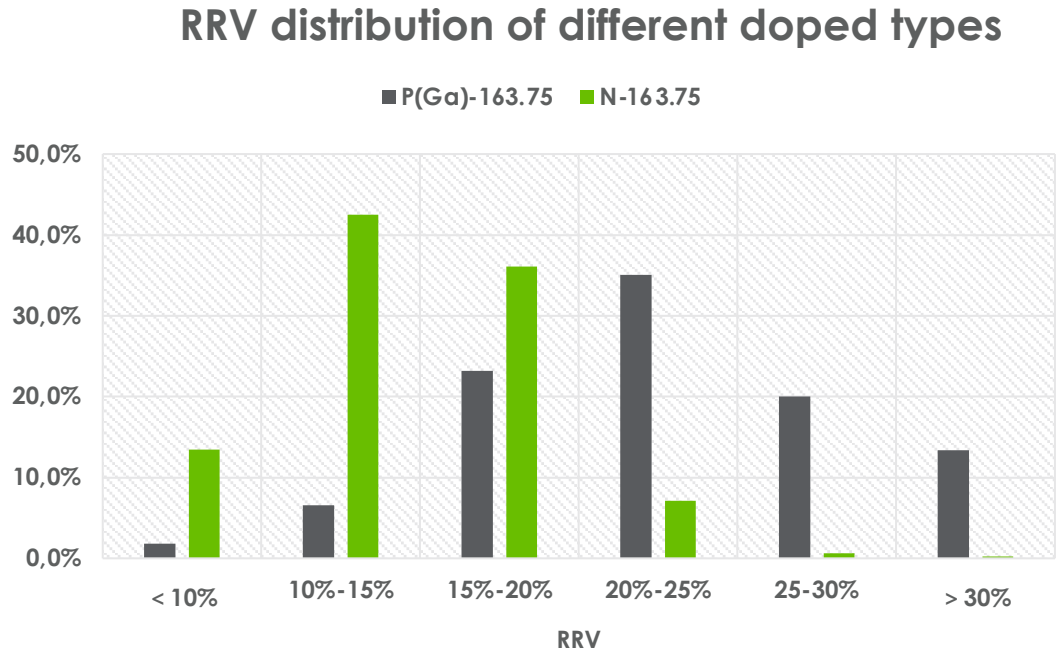
Research and Development → Supply Chain and Logistics → Manufacturing and Facilities → Product Use → End of Life

- First-Class Components
- Guaranteed Quality
- Optimized Cost Structure
- Sustainability Complete System

Industrial challenges:
Ingot –wafer- and final quality



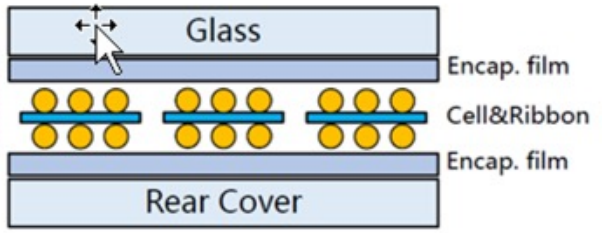
- **Uniform Growth:** The solidification at the ingot growth interface is consistent, mantaining **uniform resistivity**
- **Vertical Cutting Impact**: Vertical wafer cutting introduces varied resistivity across different points on the wafer.
- **Larger sizes, larger differences:** he resistivity variation intensifies with larger wafer sizes
- **n-type vs.p-type:** due to the segregation coefficient difference, **n-type wafers are more uniform.**



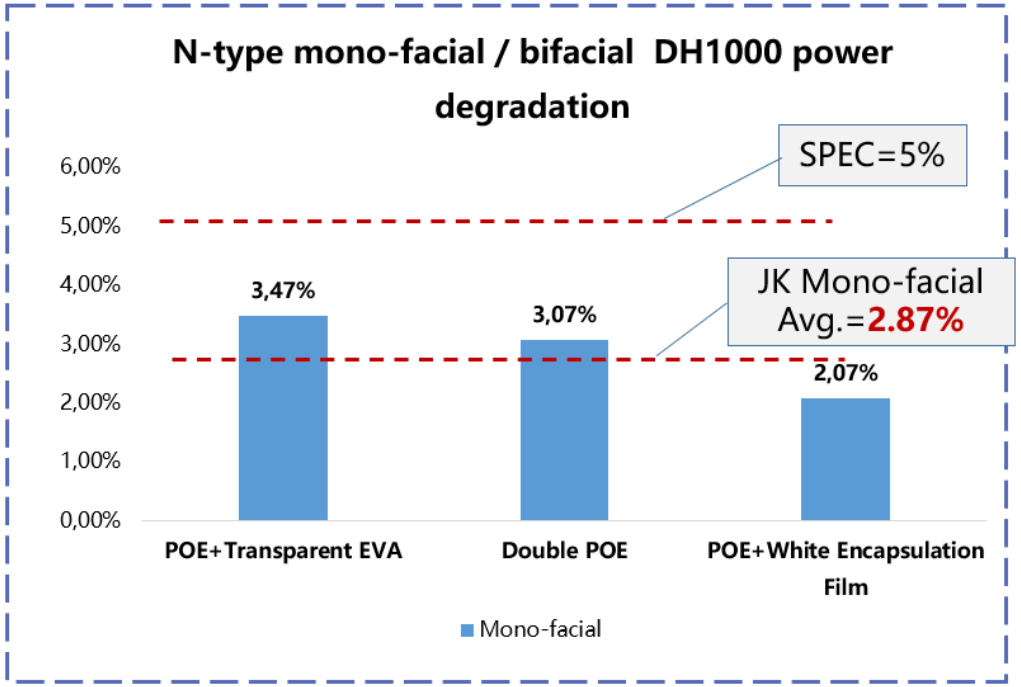
- The RRV (radial resistivity variation) value of the P type wafers with Ga doped is higher than the N type wafers with P doped.
- As the wafer size increases further, **RRV challenge for p-type is more severe than n-type**.

Industrial challenges:
BOM selection- Encapsulant

n-Module Encap. Trend



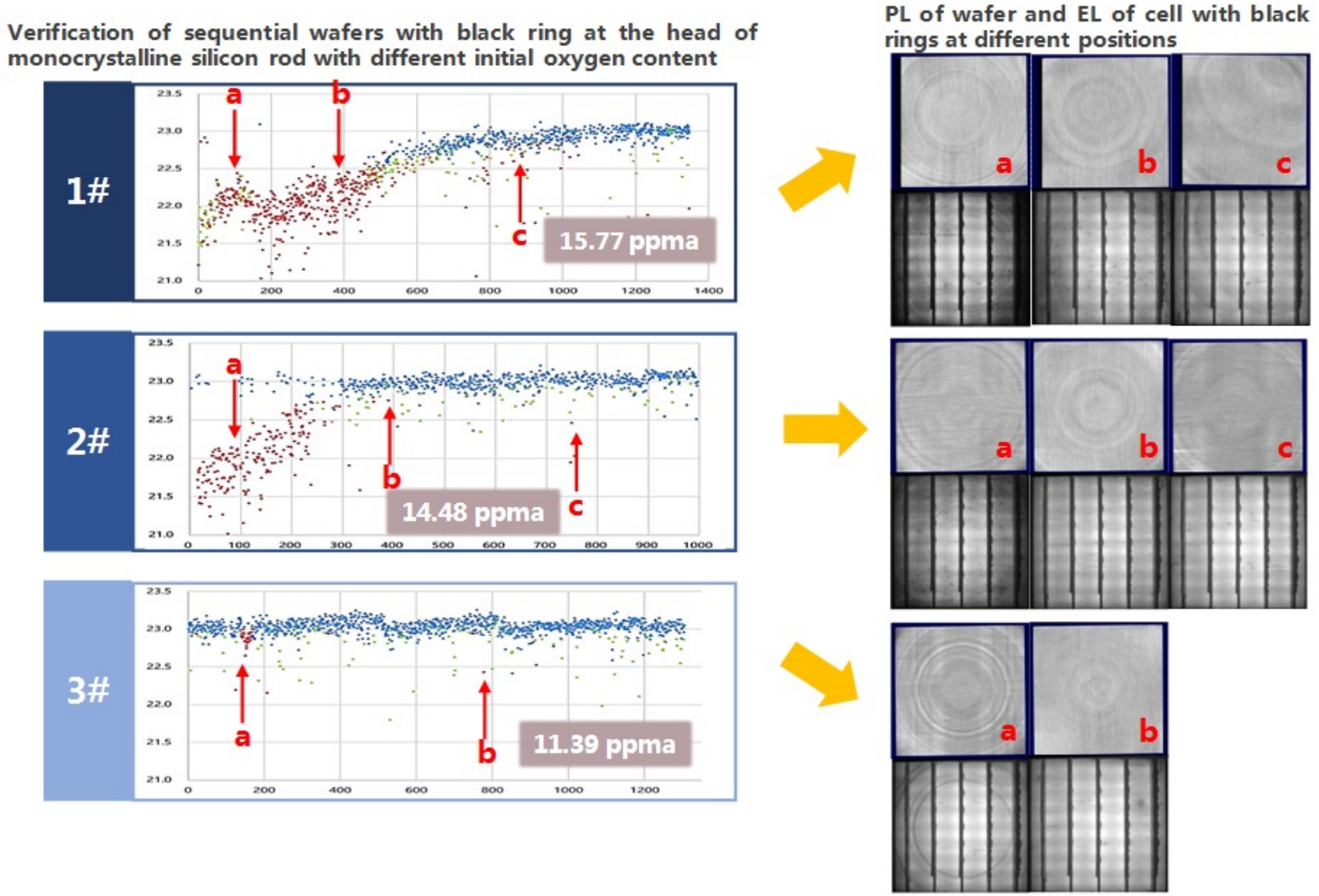
	EVA	POE
Manufacturing difficulty	*	**
Curing Speed	***	**
Adhesion to Glass	***	**
Reliability	***	***
Anti PID	**	***
WVTR	*	**
Cost	**	***



- **Supply chain**: Cost & reliability
- **Feasibility:** implementation at mass scale production
- **Continuous improvement** on-going materials/processes

Industrial challenges:
n-type wafer EL “ring” effect

- Ring effects under EL is a well-known phenomena for n-type, with no impact in power.
- Strong correlation with the oxygen concentration in wafers; oxygen precipitation.
- **While low oxygen ingot growth technology developing, product performance study and new standards are widely discussed.**



IEC working groups for EL defects on TopCon: WG8 for Cells & WG2 for module

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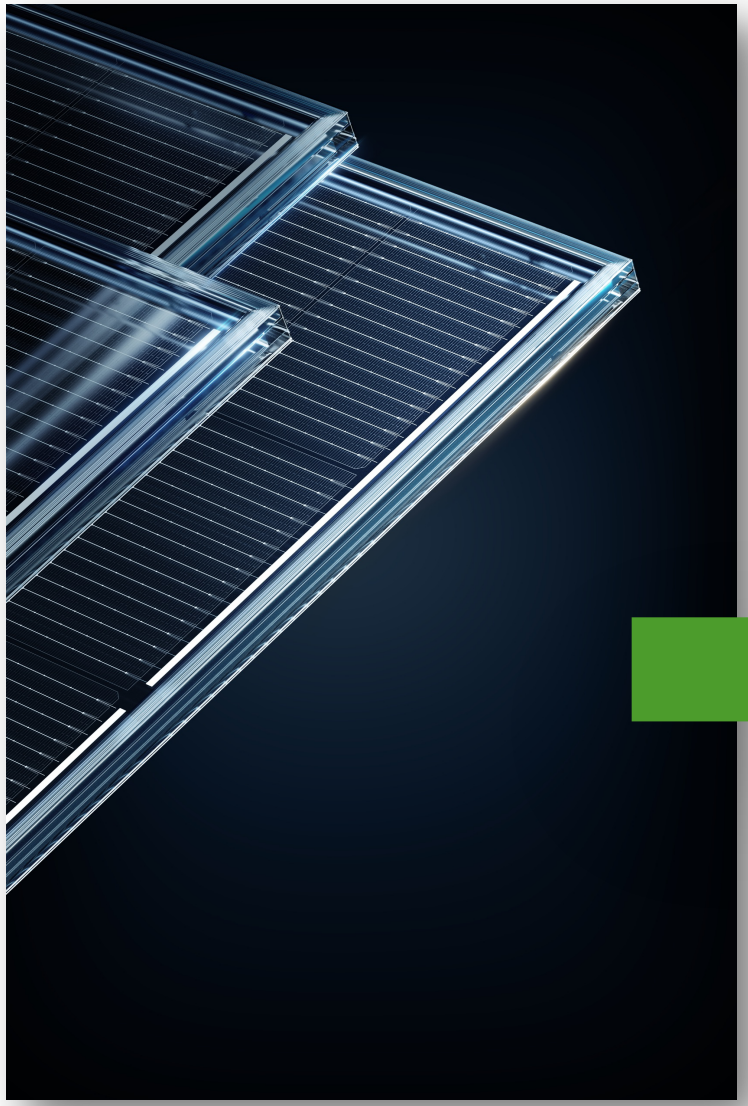


Strategies for Success: In-depth grasp of critical parameters

Well equipped R&D center enables comprehensive analysis & investigation

Characterization & monitoring

Material Characterization

Optical: refractive index, Transmittance, extinction coefficient, etc.

Electrical: doping, resistivity, carrier concentration, mobility, etc.

Microstructures: micro-thickness, crystallization, chemical composition, surface morphology, etc.

Process Control

Wet Chemistry: concentration, contamination, weight loss, etc.

Diffusion and thin film deposition: temperature profiles, gas flow, appearance, etc.

Metallization: weight, line shape, drying and sintering, etc.

Device Analysis

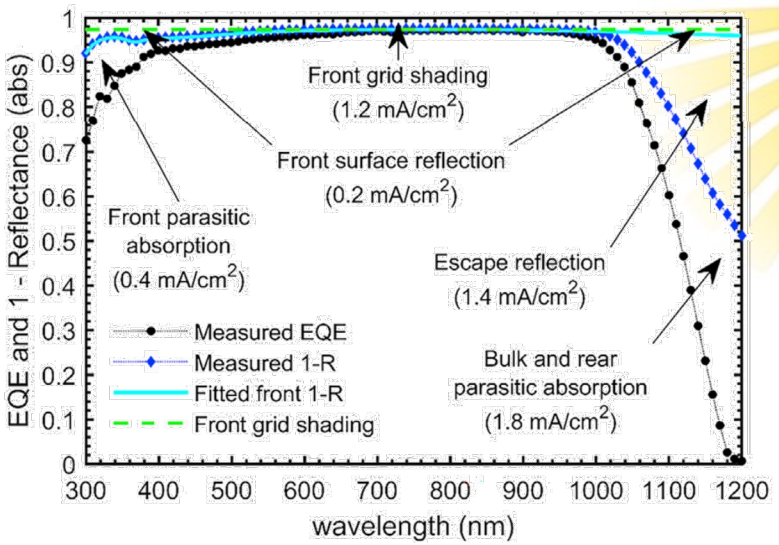
Passivation system : lifetime, PL, EL, J_0

Optical system: film design, shading, EQE

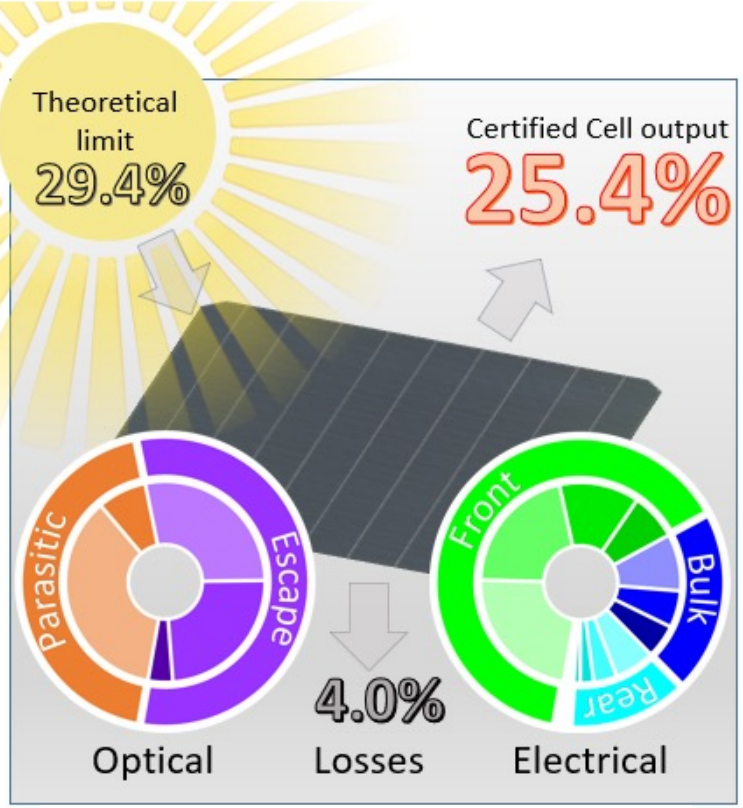
Electrical: TLM, Rs mapping, pFF analysis

Strategies for Success: In-depth grasp of critical parameters

Optical Losses Analysis [3,4]

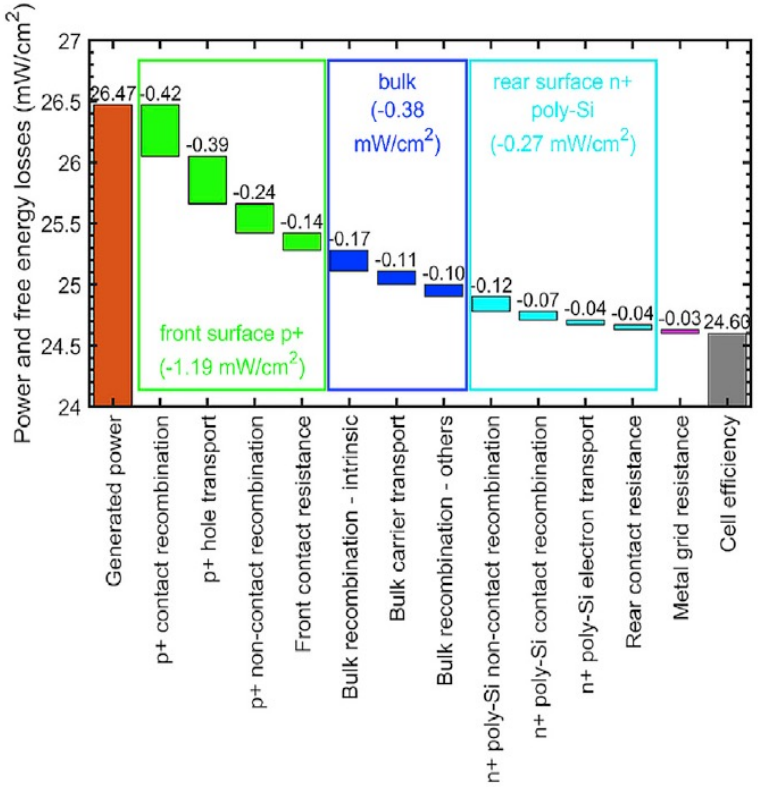


- **Significant optical losses:** bulk and rear parasitic absorption; escape reflection.
- **Potential solutions:** thinner films, optimized coating



November 2021 champion cell

Electrical Losses Analysis [3,4]

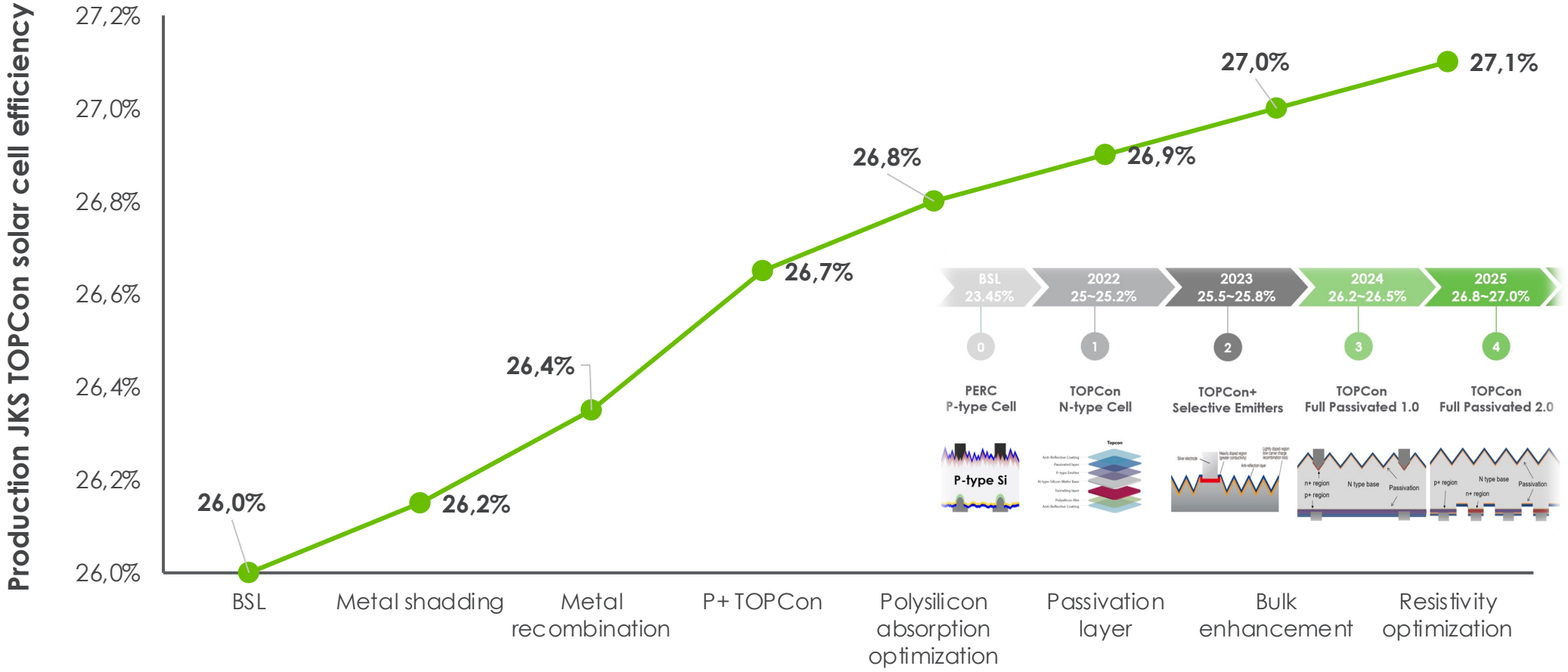


The **boron-diffused region on the front surface** accounted for losses of **1.19mW/cm2, representing 63% of the total losses**

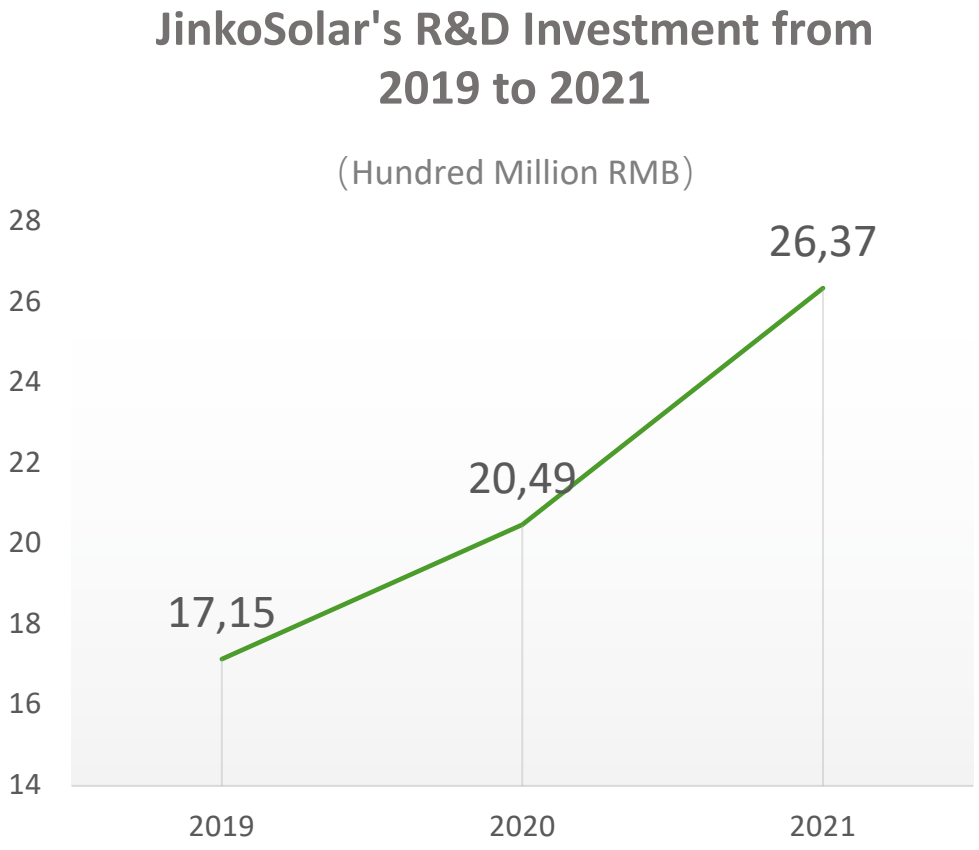
[3] Zheng P, Yang J, Wang Z, et al., "Detailed loss analysis of 24.8% large-area screen-printed n-type solar cell with polysilicon passivating contact," Cell Reports Physical Science 2, vol. 100603, October 20, 2021, doi: 10.1016/j.xcrp.2021.100603.
[4] Bonilla J, Giehl R, Magistris C and Murgioni R. TOPCon efficiency breakthrough from cell to PV modules. Photovolatics International Ed. 48

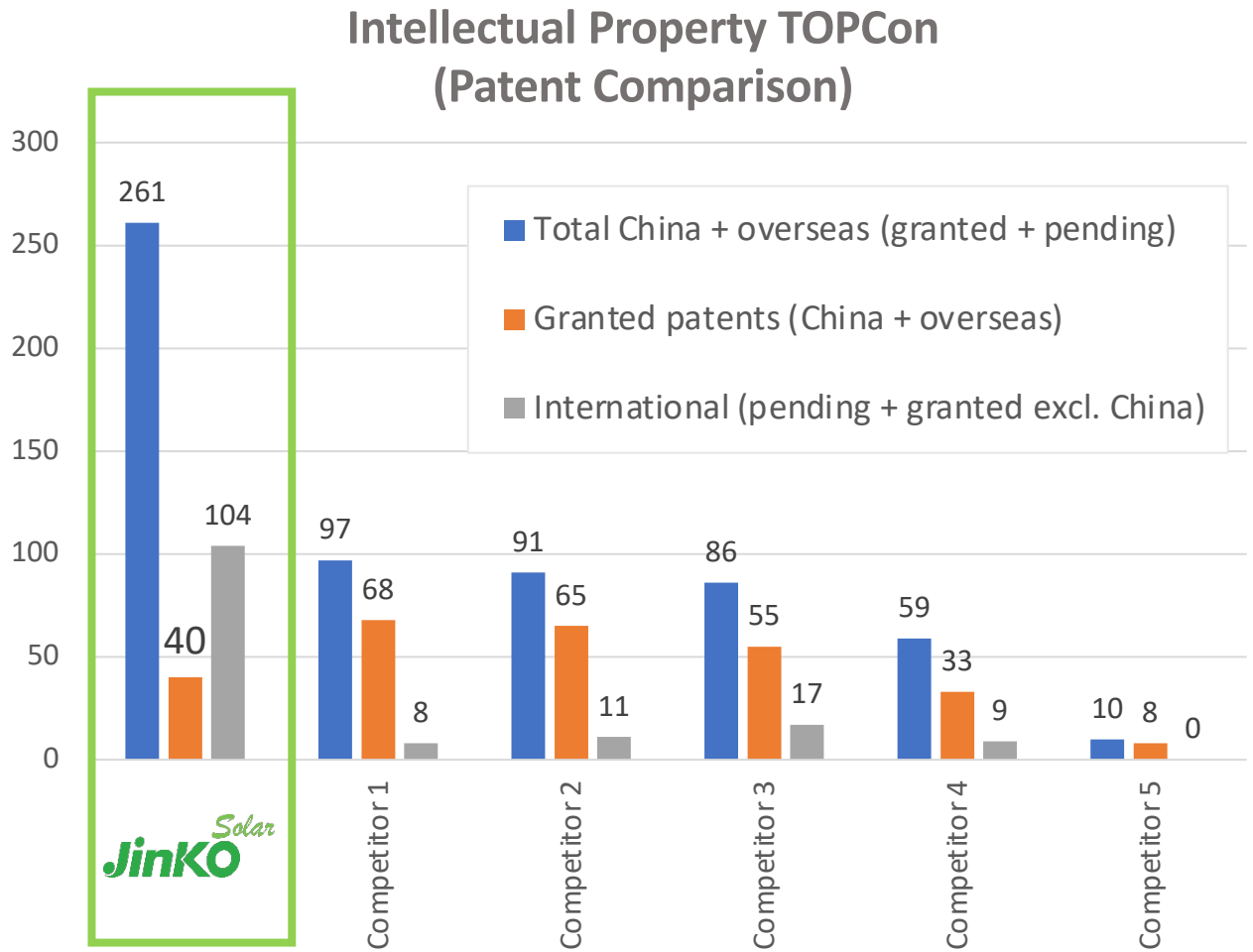
Strategies for Success: Practical path

Steps towards >27% TOPCon solar cell in the near future



Strategies for Success: R&D Investment and Patent Forging

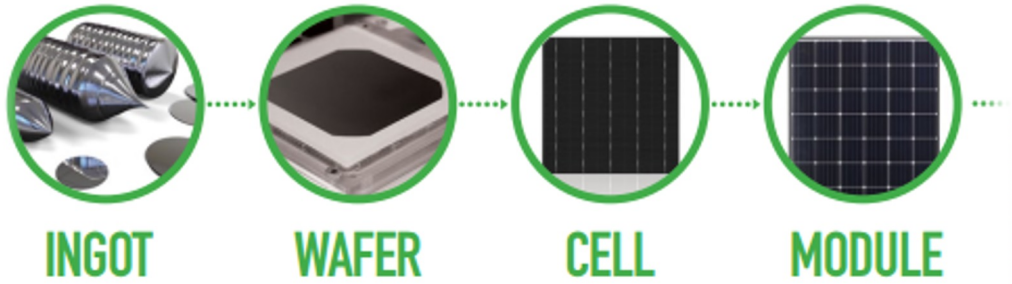


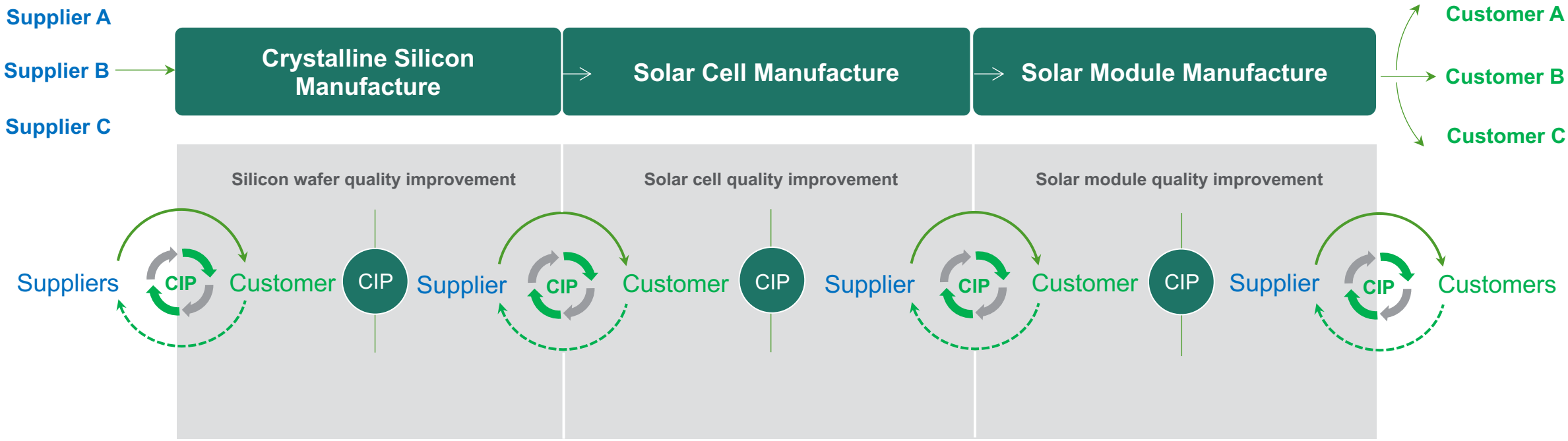


Source: before 2023/11 based on PatSnape public database..

Strategies for Success: Production Quality & Quality Assurance

- Rigorous control over suppliers, production processes, and customer satisfaction
- Strong interaction between key departments (R&D, QA and Production)
- Pilot lines before mass production

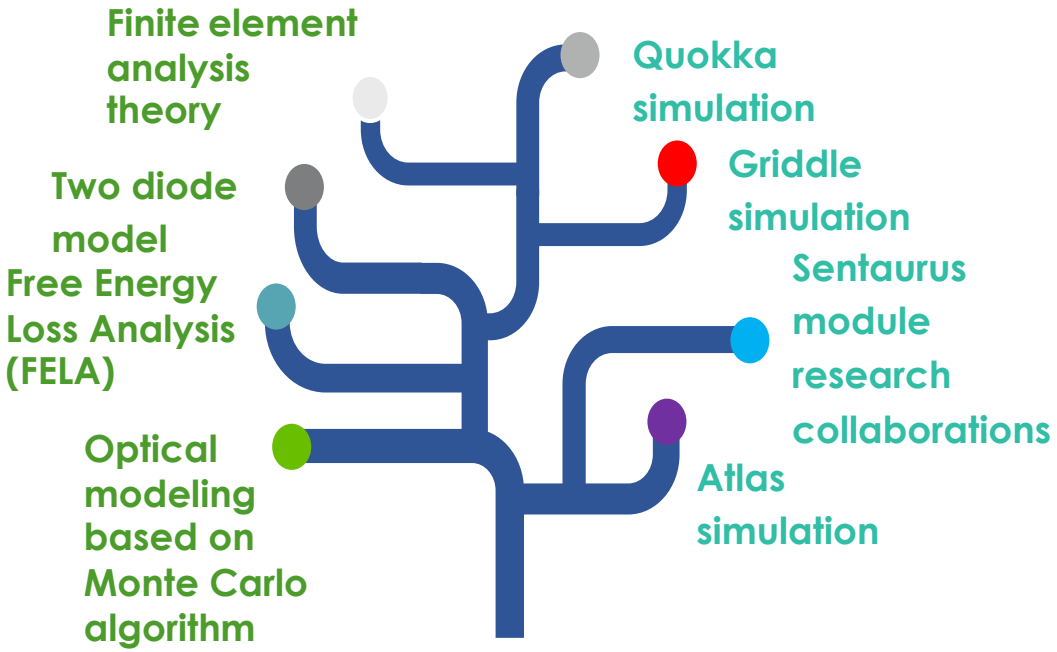




Strategies for Success: Data & More Data

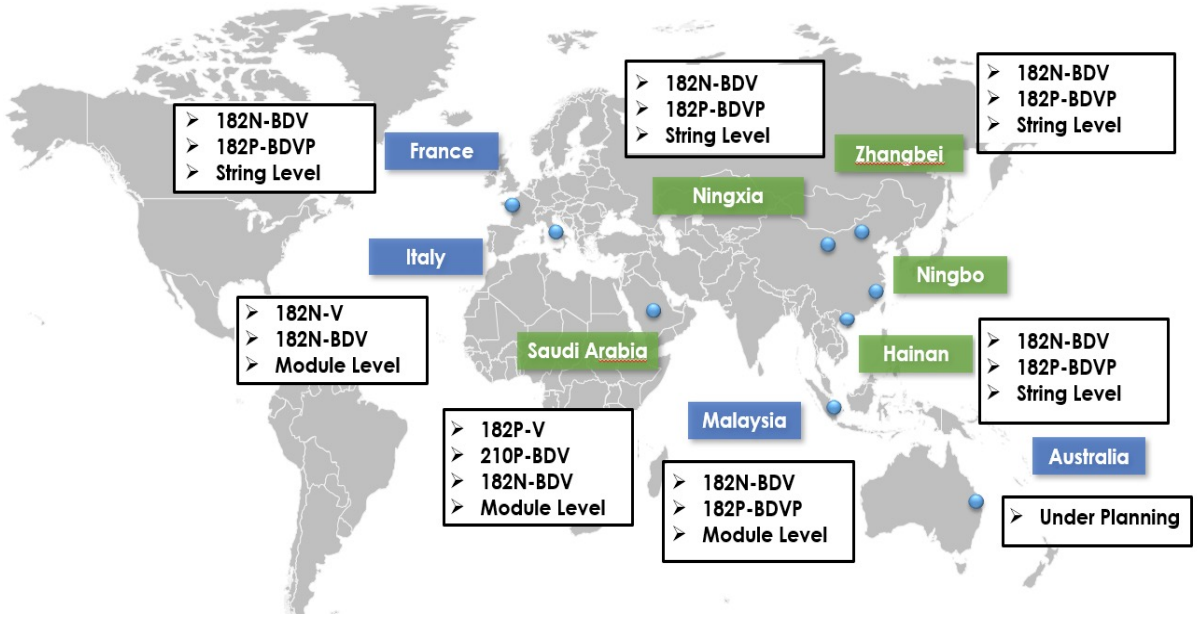
Strong R&D

fundamental research & simulation



Worldwide Field Tests

Energy yield & long-term performance



Strategies for Success: Testing & more testing

Historical Scorecard

The table below shows the history of top performance for all manufacturers featured in the 2023 Scorecard. Manufacturers are listed by the number of years they have been designated a Top Performer, in alphabetical order.

TOP PERFORMER 2023 PVEL member of group kiwa PV MODULE RELIABILITY SCORECARD

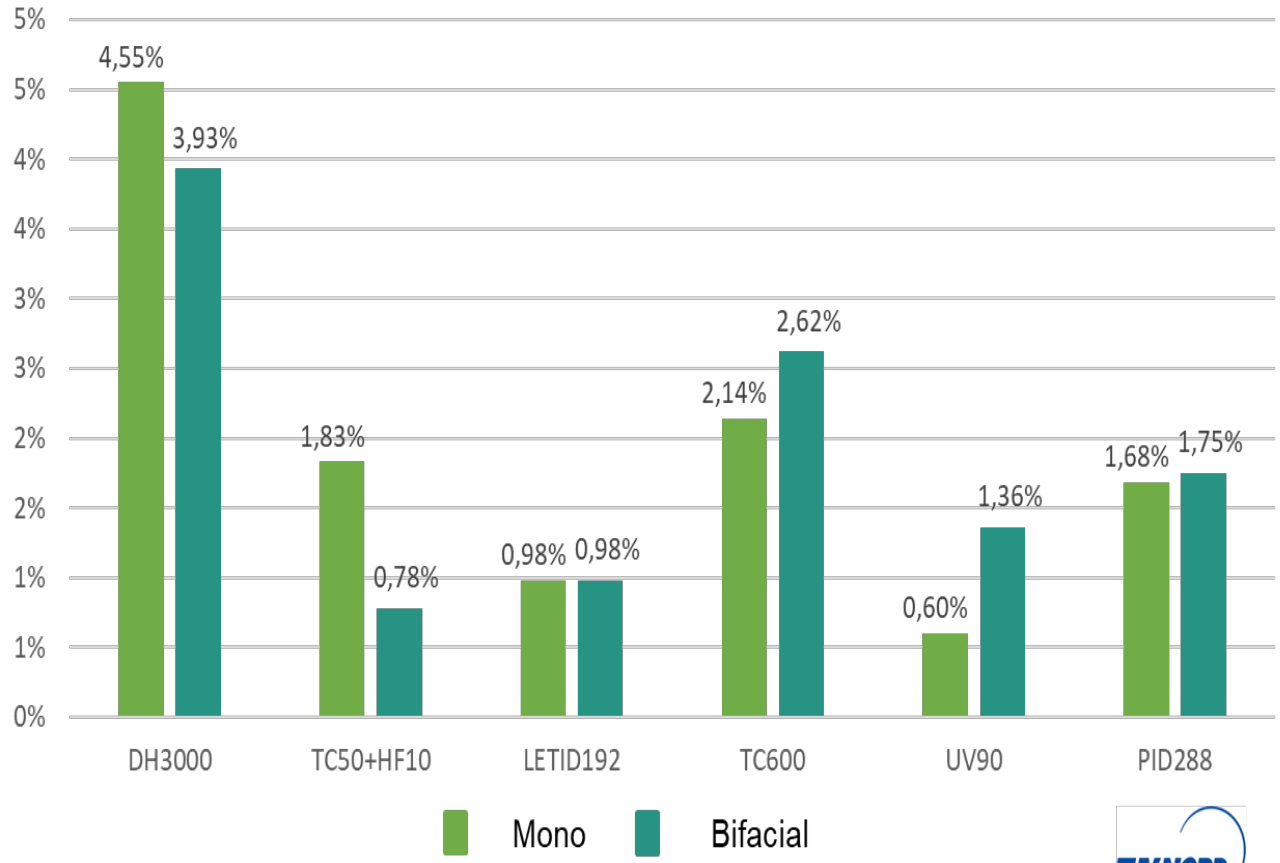
	2023	2022	2021	2020	2019	2018	2017	2016	2014
Jinko	•	•	•	•	•	•	•	•	•

Factory Witness, Characterizations and Light-Induced Degradation Measurement

Thermal Cycling	Damp Heat	Backsheet Durability Sequence	Mechanical Stress Sequence	Hail Stress Sequence	Potential-Induced Degradation	LETID Sensitivity	PAN File & IAM Profile	Field Exposure
TC 200	DH 1000	DH 1000	Static Mechanical Load	Hail	85°C, 85%RH MSV (+ and/or –) 192 hrs	LETID 162 hrs (75°C, Isc-Imp)	PAN File	Field Exposure 6 Months
Characterization	Characterization	UV 65 kWh/m²	Characterization	Characterization	Characterization	Characterization	IAM Profile	Characterization
TC 200	DH 1000	Characterization	Dynamic Mechanical Load	Dynamic Mechanical Load		LETID 162 hrs (75°C, Isc-Imp)		Field Exposure 6 Months
Characterization	Characterization	TC 50 + HF 10	Characterization	Characterization		Characterization		Characterization
TC 200	Stabilization 80°C, Isc, 48 hrs	UV 65 kWh/m²	TC 50 + HF 10	TC 50 + HF 10		LETID 162 hrs (75°C, Isc-Imp)		
Characterization	Characterization	Characterization	Characterization	Characterization		Characterization		
		TC 50 + HF 10						
		UV 65 kWh/m²						
		Characterization						
		TC 50 + HF 10						
		UV 6.5 kWh/m²						
		Characterization						

https://scorecard.pvel.com/top-performers/

Three Times Reliability Test



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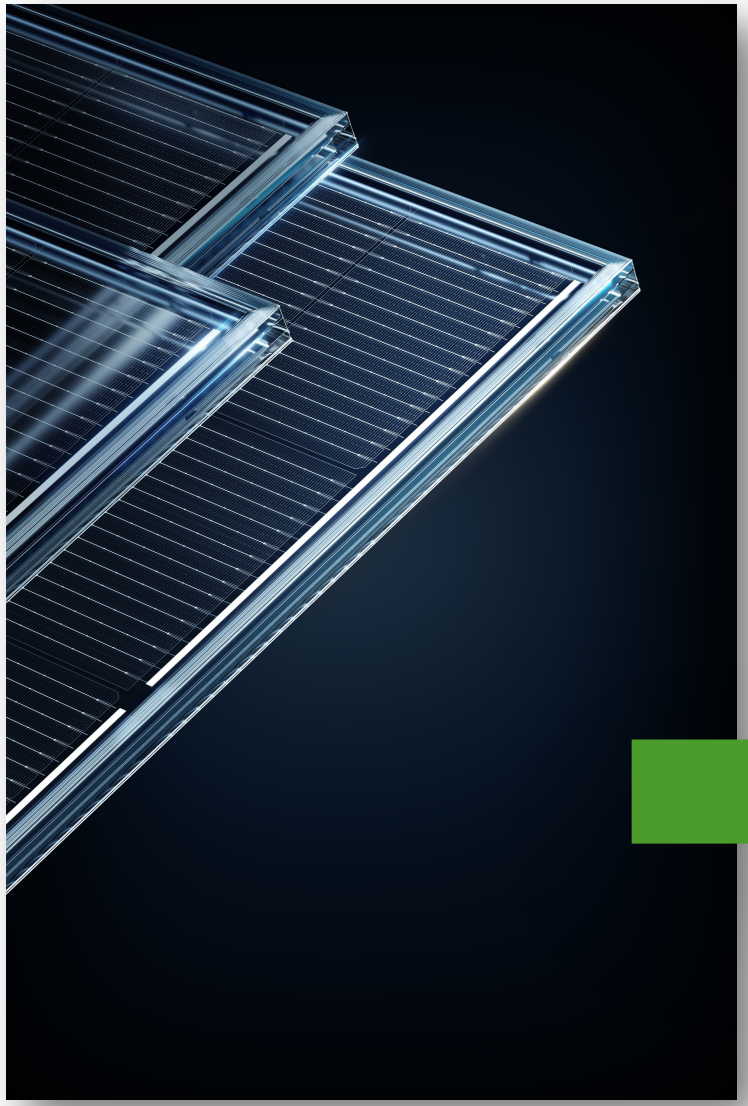


Conclusions: JinkoSolar and TOPCon

- **Foundation in R&D:**
  - **Robust** - cornerstone before product launches.
  - **Proactive** measures are taken to address potential issues and ensure seamless integration.

- **Continuous Learning Process:**
  - Mass production involves a learning process.
  - **Correction** is acknowledged as part of the process, **but emphasis on proactive quality check & prevention**.

- **Committed decisions:**
  - Decision driven by **data, test and long-term realistic goals**

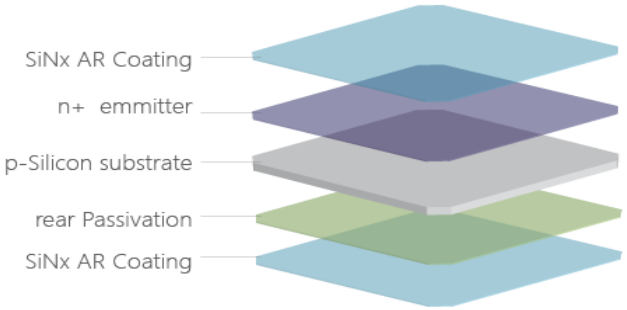
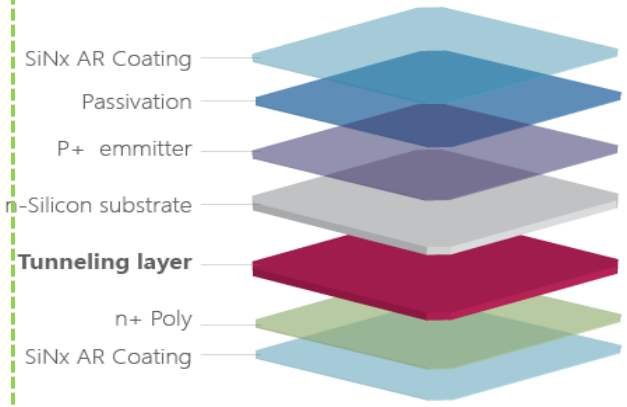
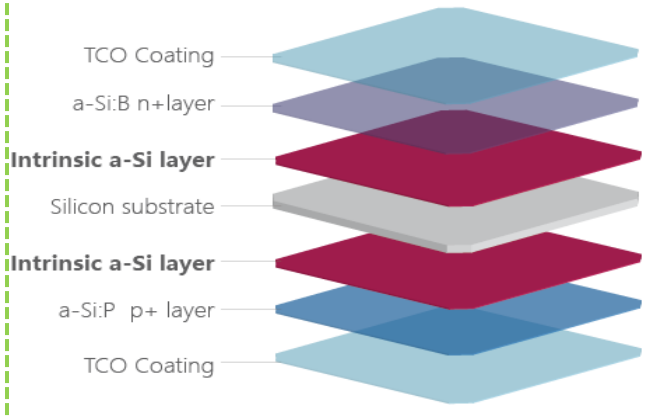
- **Readiness and Resilience:**
  - Challenges require **mitigation, innovation and dedications to quality.**

Thank you!

Johanna Bonilla

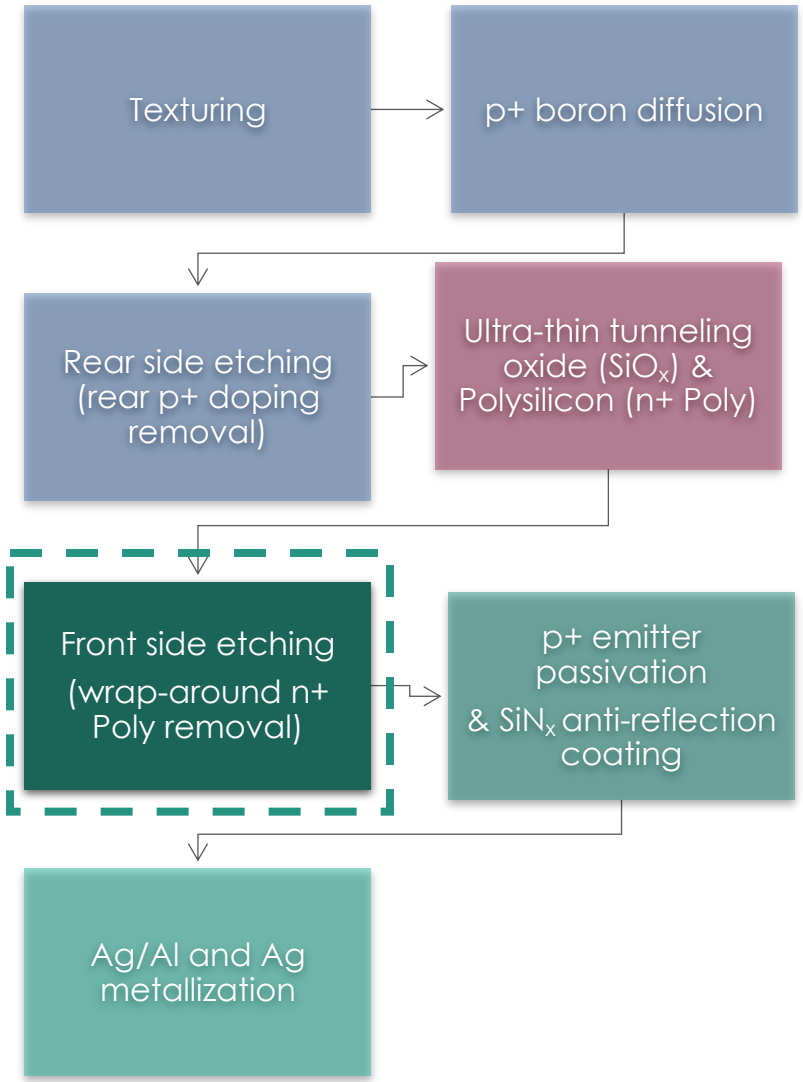
Technical Product Manager Europe

Technical Roadmap: Why TOPCon?

	PERC	Topcon	HJT
			
Theoretical Ultimate Efficiency [1,2]	24.5%	**28.7%**	28.5%
Temperature Coefficient	~-0.34	~-0.29	**~-0.27**
Bificiality	~70	~80	**~85**
PID Risk	PID-p	PID-p	PID resistant
Delamination Risk	Low	Low	High
Moisture Sensitivy	**	***	*****
Hot Spot Risk	**	**	*****
Cost	BSL	~BSL	**+~3cent/W**

[1] Brendel, R., Rienaecker, M. & Peibst, R. 2016, "A quantitative measure for the carrier selectivity of contacts to solar cells", Proc. 32nd EU PVSEC, Munich, Germany, doi:10.4229/EUPVSEC201620162CO.4.1.
[2] Brendel, R. & Peibst, R. 2016, "Contact selectivity and efficiency in crystalline silicon photovoltaics", IEEE J. Photovolt., Vol. 6, No. 6, pp.1413–1420, doi:10.1109/JPHOTOV.2016.2598267.

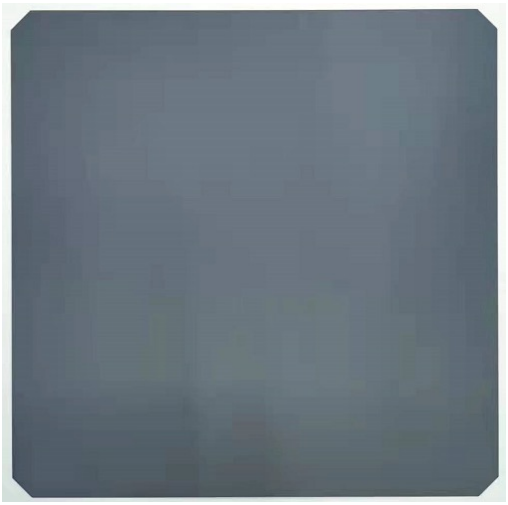
Industrial challenges:
Cell process Wrap-around n+ poly removal



➢ **Removal:** Since polysilicon is inherently deposited on both sides of the wafer, a wrap-around etching using mass production feasible chemical wet-bench is performed. Using appropriate process control, the front side p+ emitter can be well protected

Before

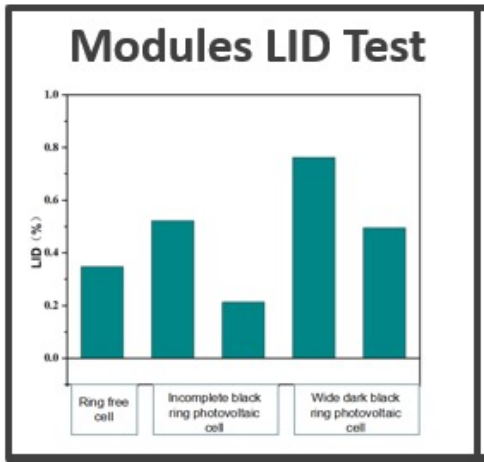
After

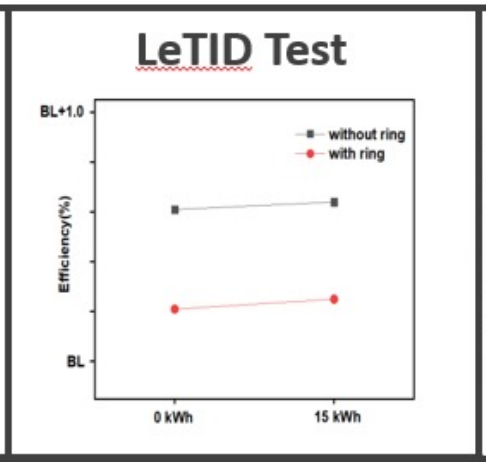


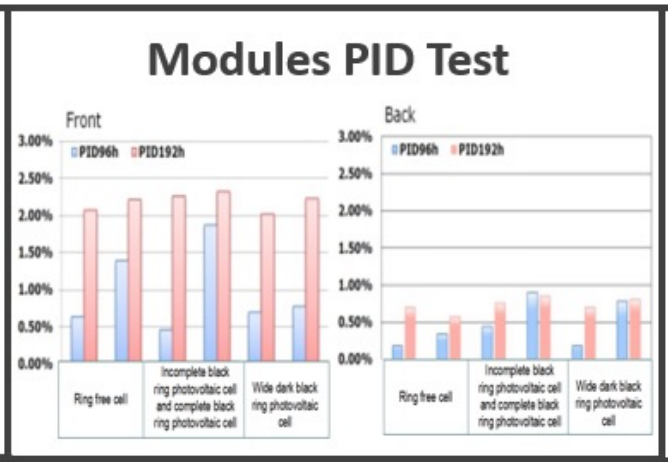
The front side borosilicate glass (BSG) and the rear side phosphosilicate glass (PSG) layers are removed in diluted HF solution

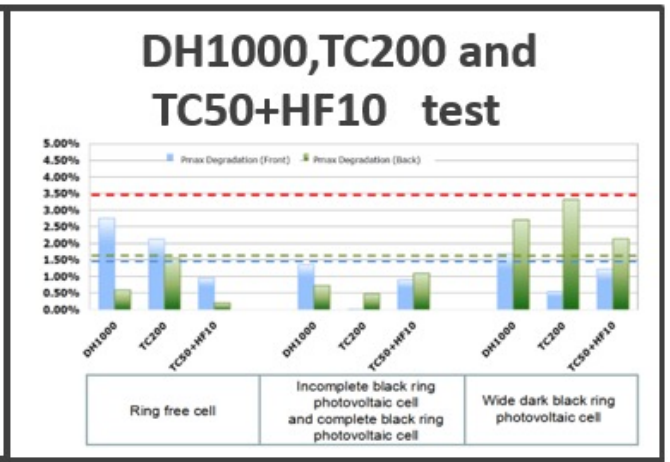
Industrial challenges:
n-type wafer EL “ring” effect

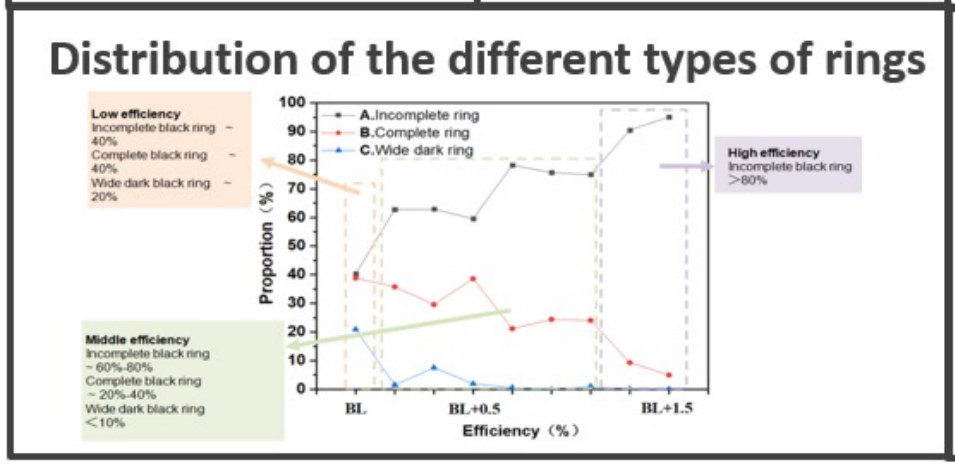
Various performance comparison study between cells with and without ring effects demonstrate **no clear correlation between rings effects with degradation problems.**

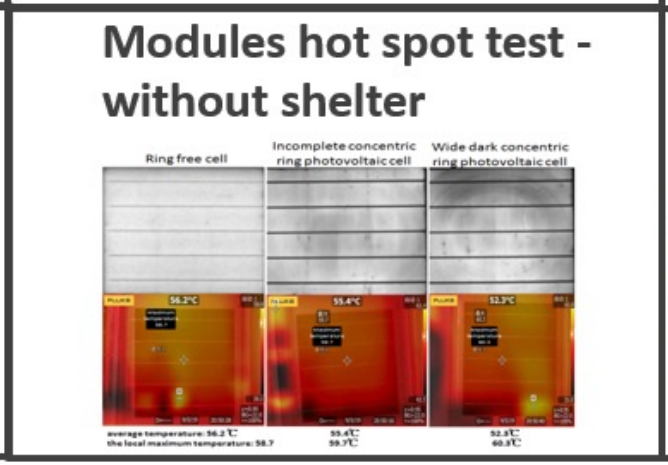


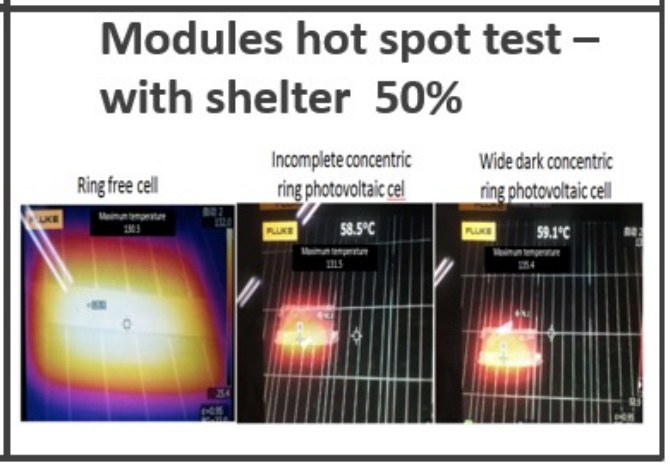








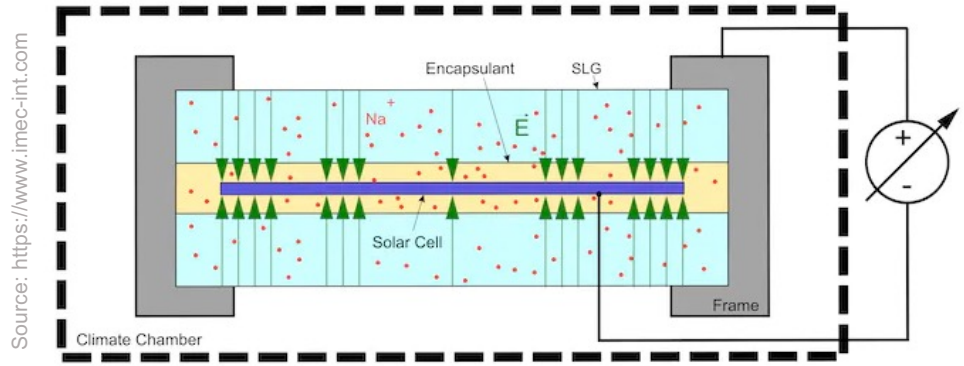




[IEC working groups for EL defects on TopCon: WG8 for Cells & WG2 for module]

Tiger Neo Utility — Enhanced reliability

Potential-Induced Degradation (PID)



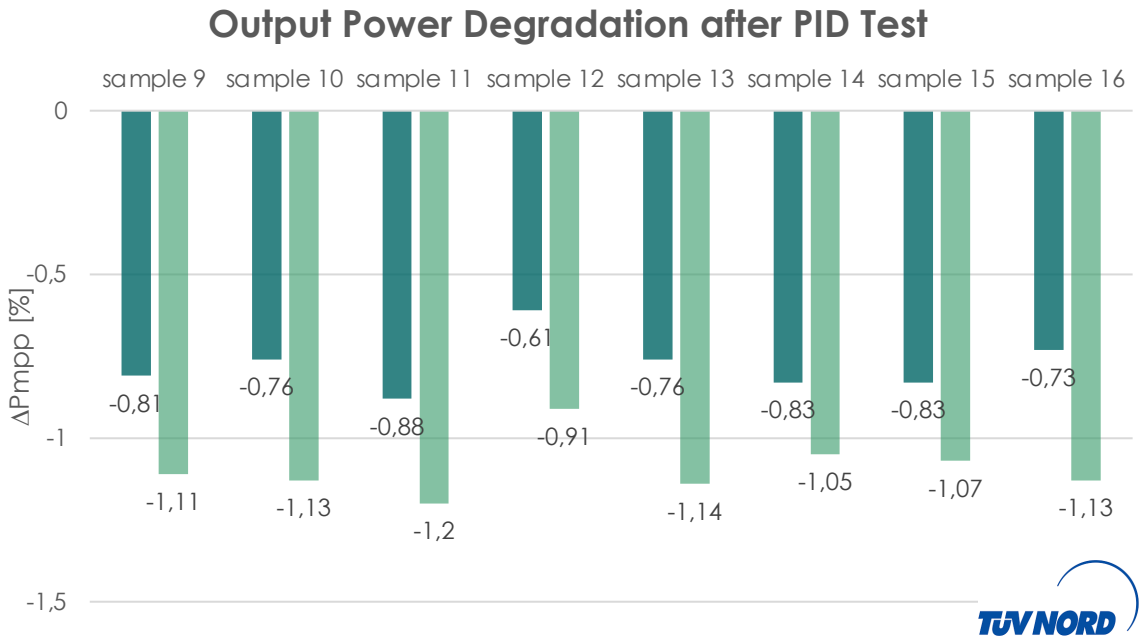
PID: ion drift (mostly sodium, Na) towards the solar cell under influence of a strong electric field (green arrows).

What?
- **PID-s (shunting):** Sodium ions diffusing into silicon stacking faults &shunting the cell
- **PID-p (polarization):** temporary & reversible degradation of the passivation layer, due to a surface recombination increase

Why?
- Expose to frequent high- voltage stress causing power drop

TOPCon
- PID-p senstivity
- Bifacial cells in glass/glass are more sensitive
- Thinner layers also seem to be more sensitive

PID 3rd party results for JKS Dual Glass Modules



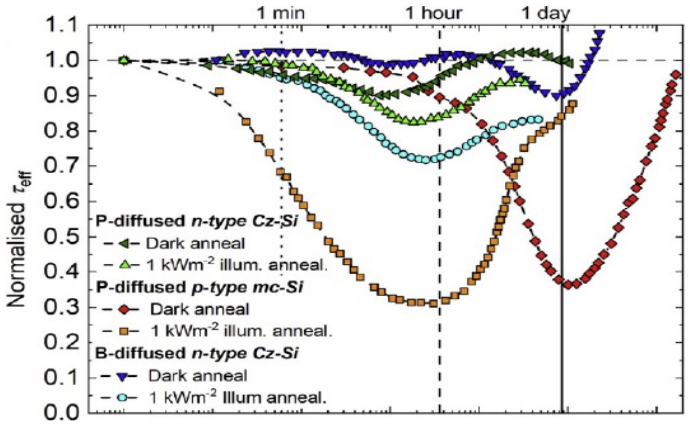
Module type: JKM550N-72HL4-BDV

ΔPmpp [%]	After 96h	After 192h
Min	-0,61%	-0,91%
Max	-0,88%	-1,20%
Average	-0,78%	-1,09%

Tiger Neo Utility — Enhanced reliability

Light and elevated Temperature-Induced Degradation (LeTID)

LeTID Degradation Comparison & Recovery in boron and phosphorus diffused n-tyüe Cz-Si and phosphorus diffused p-type mc-Si



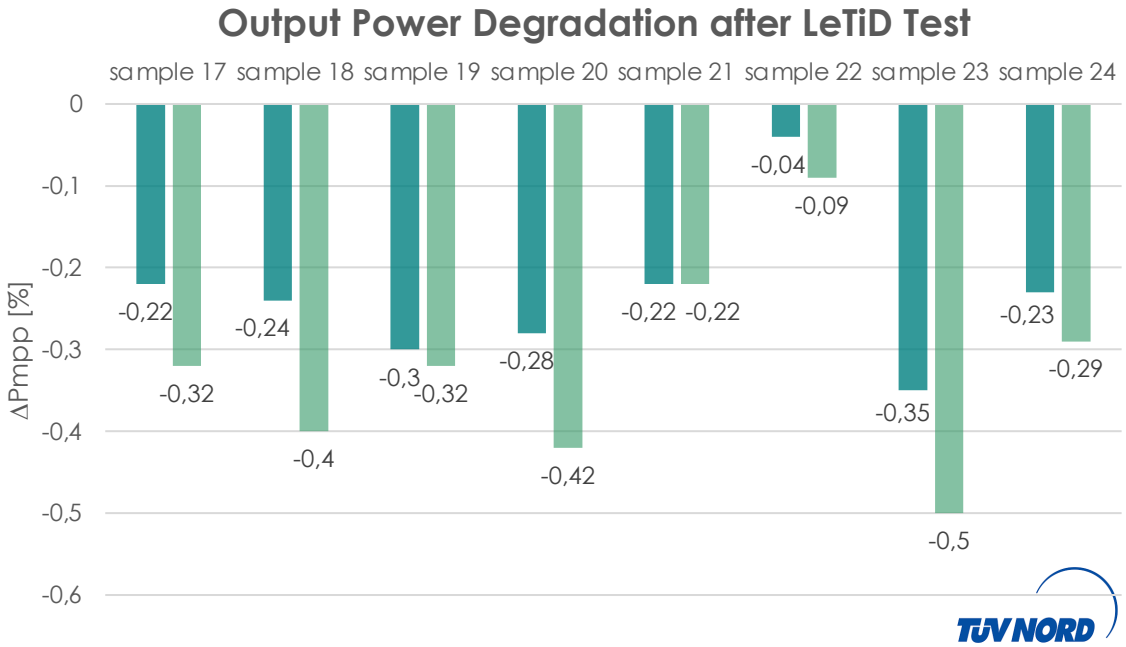
Source: Daniel Chen et al., doi: 10.1016/j.solmat.2019.110353

What?
- **Phenomenum not a fundamental mechanism-** it could be observed & measured . It is a temperature driven condition as a result of hydrogenation

Why?
- **high irradiance at higher temperatures after hundreds of hours of light exposure**

TOPCon
- Presence but limited due to absence of BO LID
- Firing- induced degradation in the SiOx/n+Poly passivation
- Hydrogenation- critical for chemical passivation for SiOx/n+Poly

LeTID 3rd party results for JKS Dual Glass Modules

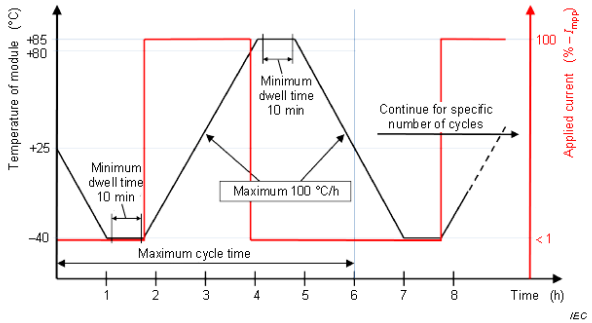


Module type: JKM595N-78HL4-BDV

ΔPmpp [%]	After 300h
Min	-0,38%
Max	-0,45%
Average	-0,42%

Tiger Neo Utility – Enhanced reliability

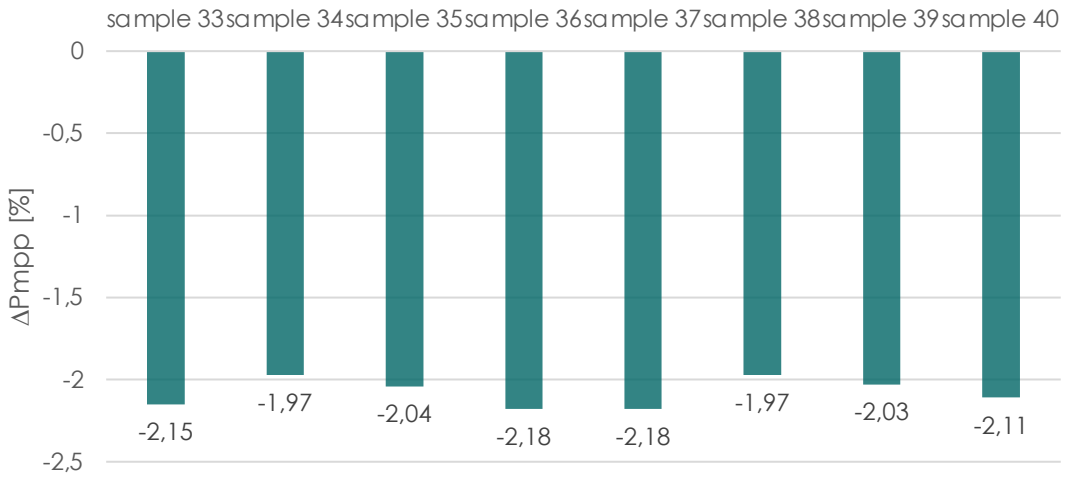
Thermal Cycling (TC)-400



Module type: JKM550N-72HL4-BDV

ΔPmpp [%]	After 400 cycles
Min	-0,38%
Max	-0,45%
Average	-0,42%

Output Power Degradation after TC400 testing

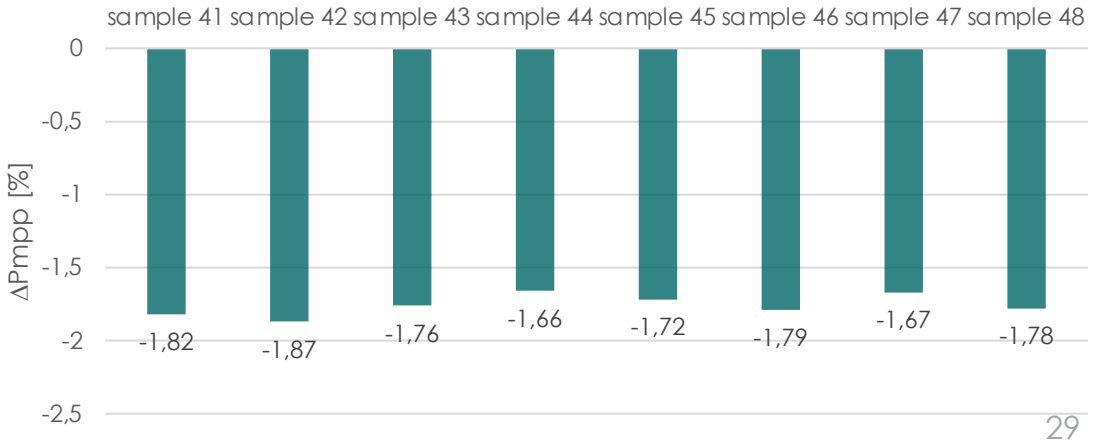


Damp Heat (DH)-2000

Module type: JKM550N-72HL4-BDV

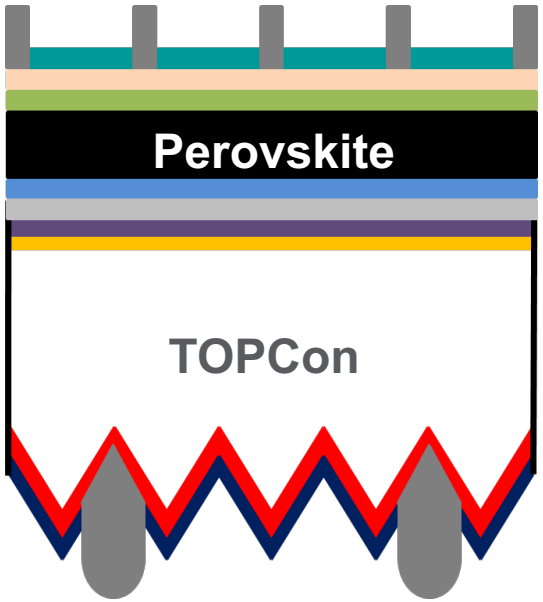
ΔPmpp [%]	After 2000h
Min	-0,38%
Max	-0,45%
Average	-0,42%

Output Power Degradation after DH2000

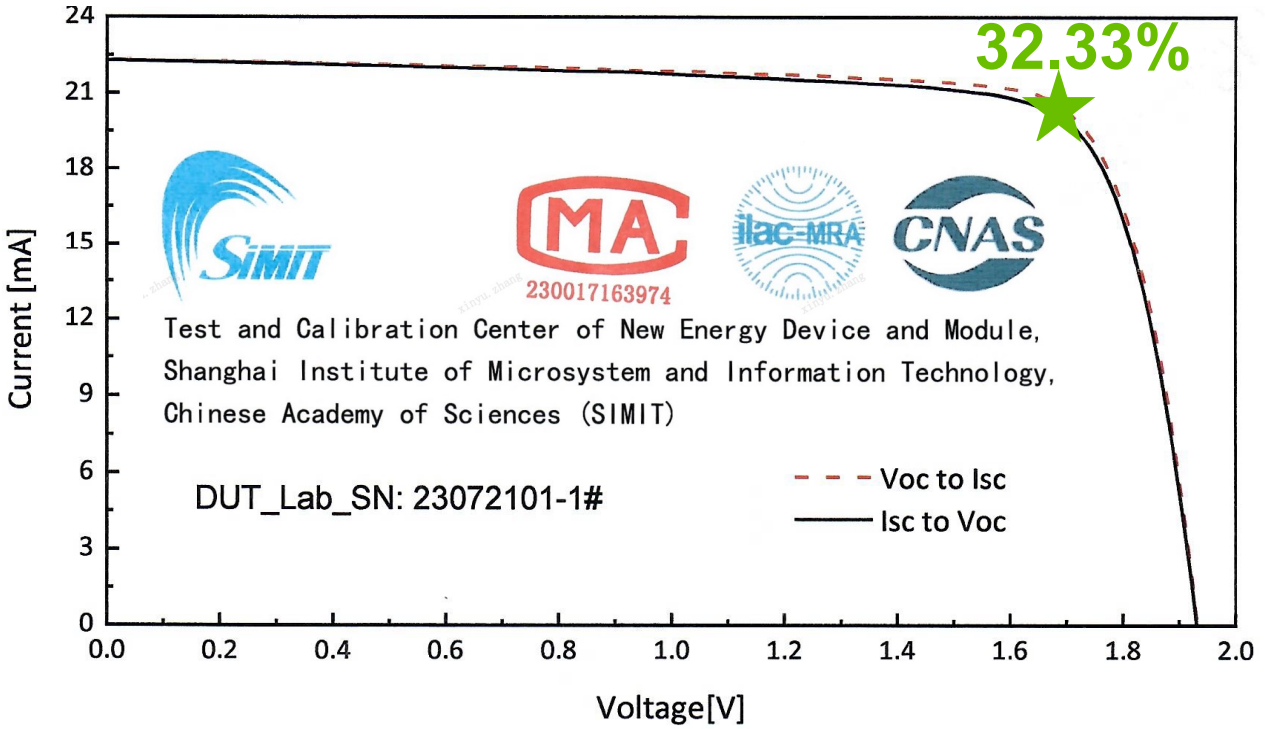


Technical Roadmap: Development trend

JinkoSolar's **New Cell Efficiency Record of 32.33%** achieved on perovskite/TOPCon tandem



Boosting PCE



① **Surface passivation**: optimization of the passivation layer

② **Bulk passivation**: additive engineering to lower the hysteresis effect

③ **Recombination layer optimization**: high quality TCO with low resistance